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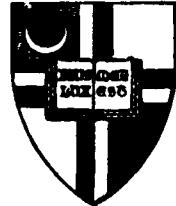
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RESEARCH ON FLOW SEPARATION  
IN WESTERN EUROPE

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Research on Flow Separation in  
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Introduction

This paper reports a survey of research activities on Flow Separation in Western Europe and West Berlin, made in the late summer of 1962. The limits of a short academic vacation (August 11-September 29) did not make it possible to meet all appropriate scientists; nevertheless the essentials of European research activities can be presented.

The major scientific countries--France, Germany, and especially England-- are well aware of the importance of the problems of flow separation, and have engaged extensively in research, although an emphasis expressed by Prof. L. Lees in the U.S.A. is lacking. Prof. Lees, presenting his paper on hypersonic wake flow at the annual meeting of the Institute of the Aero-Space Sciences in New York in December, 1961, told his audience that the problem of flow separation will become one of the most fashionable in the near future. Model basins and hydrodynamics institutes in European countries are very much interested in the problems of flow separation, but except for the Institut für Schiffbau der Universität, Hamburg, and in limited scope at Skipmodelltanken, Trondheim, Norway, it is felt that no special research on this subject has been carried on. Hence, most of the work listed in the following pages was done at the aerodynamic institutes.

The main emphasis in research is placed on the fields of (1) Flow Separation on Swept Wings, (2) Base Flow, (3) Interaction between Shock Wave and Boundary Layer, and (4) Generalized Concept of Flow Separation.

(1) Flow Separation on Swept Wings.

In recent years in Europe, notably in England and France, research in the regions of transonic and supersonic speeds have been concentrated on the aero-dynamic design of aircraft with highly swept wings. On highly swept wings flow

separates from the leading edges. Hence the influence of leading-edge radius, and of angle of sweep-back, on the development of leading-edge vortices and on vortex flow, is the subject of many of the experimental investigations that have been and are under way. Also, an analysis is being completed which develops an approximate method of calculating the non-linear lift on an aircraft wing with leading edge separation.

(2) Research on Base Flow.

Wing sections with thick trailing edges may delay the onset of shock wave drag and also shock induced boundary layer separation. But unless the large base-drag penalty associated with it can be reduced, thick trailing edges may not be suitable for practical use. Therefore, the physical nature of flow in the neighborhood of blunt bases has been studied with an eye to reducing the drag penalty by increasing the base pressure. It is known that one of the most effective ways of increasing the base pressure at supersonic speeds is to inject air into the low pressure cavity behind the base, thus reducing the expansion of the external air into the wake. Research on the base pressure and heat transfer behind steps, axial symmetrical bodies, and in cavities, is being carried forward in many European countries.

(3) Researches on Interaction Between Shock Wave and Boundary Layer, Causing Flow Separation.

In England the problems of separation due to interaction between shock wave and boundary layer, and heat transfer are being very extensively investigated by experiments and analyses.

(4) Researches on the General Concept of Flow Separation.

In France, the general concept of flow separation, which is applicable to three-dimensional as well as two-dimensional flow, has been formulated on a basis of surface

stream lines, supported by flow visualization study and mathematical analysis. In England an endeavor has been made to clarify the flow separation in three-dimensional flow.

More details of researches on flow separation in each country are reported in the following pages, quoting references and outlining future work.

A. England

Most of the work on flow separation has been done in England.

1. National Physical Laboratory (N.P.L.)

This laboratory is the finest research institution in Europe, and the basic research has been carried out in a free and international atmosphere resembling that of a University. Indeed many college professors have been trained here. The Aerodynamics Division is headed by Dr. W. P. Jones. Dr. W. P. Jones has studied unsteady boundary layer effects involving separation. He discussed the instabilities that may be induced by leading edge vortices and shock-induced separated flow, and also the stability problem connected with leading edge flow separation on thin highly swept wings at incidence (1).

Dr. G. E. Gadd now at Ship Division of NPL. During his stay at the Aerodynamics Division he worked on problems of heat transfer on laminar and turbulent separated flows (2,3). The measurement of heat transfer with free Mach number of 2.44 in the regions of separated flow formed by forward facing and rearward facing steps shows that in the separated region ahead of a forward facing step, high rates of heat transfer were measured close to the step, and heat transfer was also quite high downstream of reattachment behind a rearward-facing step. He confirmed theoretically the proposal of W. H. H. Banks that rotation can delay laminar separation and that it sometimes prevents it entirely. With free stream Mach number of 3, if the boundary layer is laminar, heating of the wall reduces the pressure gradients at the upstream end of the

region of interaction and increases the streamwise extent of the region. He concluded that for entirely laminar interaction, theory and experiment are in reasonable harmony (3,4). He analyzed the problem of interaction between a normal shock in an infinite stream and a turbulent boundary layer on a flat plate. Separation is predicted when the upstream Mach number exceeds about 1.2. This theory is confirmed by an experiment on normal shock in a pipe (5).

H. H. Pearcey worked intensively for flow separation. He investigated the onset of the effect of boundary-layer separation as it varies with Mach number for two-dimensional airfoils. A highly swept leading edge may eliminate shock-induced separation but will precipitate a type of leading-edge separation that is known to persist to supersonic speeds (6). The intensive work on shock-induced separation and technical measures to prevent shock-induced separation has been carried out by Pearcey. He studied 108 available references (7) summarizing them in 178 pages as a chapter in the book, "Boundary Layer and Flow Control" edited by Lachmann. His own 9 references have been included in this chapter. He produced a film on shock-induced separation in transonic flow to clarify the physical phenomena of shock-induced separation.

N. C. Lambourne. A qualitative visual observation of the flow over a small swept-back wing was made using a water tunnel at low Reynolds numbers. The study of flow at high incidence reveals that a part-span trailing vortex appears to be a continuation of a discrete vortex situated in the separated region (8). A further flow visualization study using a water tunnel yields qualitatively the flow phenomena over a series of sharp-edged semi-span plates having various angles of sweep and at incidence as high as 30 degrees (9). He made a brief review on the available information on the flow fluctuations and instabilities arising from the shock-induced separation over airfoils and wings. Due to the influence of these phenomena airfoils oscillate and cause

instabilities (10). He observed various phenomena of bursting--the structural change from a strong regular spiral motion to a weaker turbulent motion--in vortex flow generated from sharp, swept-back leading edge. It is found that the burst is sensitive to several factors; in particular, an increase of pressure gradient along the vortex seems conducive to the occurrence of a burst. An essential condition for bursting is believed to be a low total pressure at the axis of the laminar vortex. It is also found that the presence of a burst above the wing causes a loss of suction locally at the surface and a modification of the position of separation of the surface flow beneath the vortex (11).

H. C. Garner and associates analyzed the leading edge separation caused by flow past swept wings at high incidence. From the leading edge separation, there streams a strong spiral flow within a thick "part-span vortex layer" above the outer part of the wing. Based upon the various measurements, a comprehensive picture of the vortex layer is obtained. Coupled with a laminar separation the out flow arising from leading-edge sweep back, accounts for a predisposition to vortex flow. Local turbulence is seen to discourage the formation of the vortex layer, so that its spanwise extent is reduced by an increase in Reynolds number of stream turbulence (12). He and associates analyzed the low-speed experimental pressure distributions and surface oil-flow pattern, and discussed them in relation to the onset of separation and the distinct vortex flows that develop at high incidence. The onset of leading-edge separation on the 5% wing improves longitudinal stability, while the rearward turbulent separation on the 9% wing has a destabilizing effect (13).

J. F. Nash is a promising young scientist who is engaged in the research of base flow and free shear layer. He reviewed works on base flow with particular reference to blunt trailing-edge wings at subsonic and supersonic speeds (14). At subsonic speeds the flow in the wake of a blunt trailing-edge section is dominated at Reynolds

numbers above 50 by the formation of periodic vortices. The tests show that relation exists between the base pressure, the width of the wake and the shedding frequency. But at supersonic speeds the wake periodicity is less strong, and for Mach numbers above 1.4 the periodicity does not have any further effect on the base pressure. At a given Mach number the base pressure rises with increase of the ratio,  $\theta/h$  - the boundary-layer momentum thickness to the thickness of the trailing edge. At supersonic speeds the base pressure can be increased significantly by bleeding low velocity air into the wake (14). At present he is engaged in research to improve the base pressure relation at low ration of  $\theta/h$ , which could be a contribution to future work.

I. M. Hall and associates took the schlieren photographs in the plane of symmetry of flat nosed and hemispherical nosed bodies of revolution at free stream Mach number of 2.45 and the vortex wake was studied by the vapor-screen technique. The vortex wake tended to remain stable to higher incidence than had been found for pointed bodies. He observed instability at incidence of 15 degrees and found that the instability was more pronounced in the wake of the flat-nosed body (15).

C. S. Sinnott developed transonic airfoil theory which can be used to estimate transonic drag-rise, and the Mach numbers at which separation-effects begin (16).

## 2. Royal Aircraft Establishment, Farnborough

This institution is devoted to development work rather than basic research. Dr. Crabtree, who has been in the Aerodynamics Division, moved to become head of another division, and since then he has done no further work in the field of flow separation.

E. C. Maskell. In the past he authored a report (17) on the separation of three-dimensional fluid flow which generalized the concept of flow separation. He indicated that improvement will be made on his original work. At present he is interested in the basic problem of edge vortices.

A. Naysmith measured the local heat transfer rates in bubbles of separated flow behind rearward facing steps in supersonic air streams (18). As expected a pronounced peak in the heat transfer rate was measured at the reattachment of the flow. He built a model using a poor conducting material to reduce the heat conduction. With this model he found much higher heating rate near flow reattachment than experiments by other investigators with models of higher conductivity material. He is continuing his experimental work to measure the base pressure and heat transfer behind a cone-cylinder body at supersonic air flows with a support attached to the cone surface.

D. Küchemann in a paper presented at IUTAM Symposium Transonicum, Aachen, 1962, discussed three-dimensional flow phenomena of the transonic type. The cases considered were slender wings at Mach numbers near unity and, more extensively, conical lifting bodies at higher Mach numbers. The test shows that there exists a number of interesting flow phenomena connected with vortex formation, and an attempt was made to define them and to assess their importance in aerodynamic design.

The boundary layer control research is going on at the RAE for the development of vehicles.

### 3. College of Aeronautics, Cranfield

This college has accommodations for students who already have the bachelor's degree and would like to pursue further studies. This is a unique institution of its kind in England, but academic degrees are not offered though professional certificates are issued.

A. J. Alexander measured thoroughly the aerodynamic forces and moments for a delta wing model mounted in a subsonic wind-tunnel. This report will be published soon. At the College of Aeronautics a doctoral candidate at Imperial College, London, investigated bubble formation with and without sound energy. In the case where no sound energy is injected he found a new dimensionless parameter in addition to

Reynold's number to characterize the bubble. His work will be published also as a doctoral thesis in the near future.

4. Oxford University, Oxford

The Engineering Laboratory at Oxford is in process of expansion and a new building is being built. This laboratory, where engineering is taught and experimenting is done, carries only the basic engineering science program, and no special curriculum such as mechanical or electrical engineering is offered.

Prof. D. W. Holder, who moved to Oxford from NPL, will continue his work on the problem of flow separation. At NPL he worked with Pearcey and Gadd on the problem of the interaction of shock wave and boundary layers (19). At present the laboratory is engaged in problems of plasma physics which also involve flow separation. Recently a seminar was held on laminar separation at the institute of mathematics. The manuscript is not yet available.

5. Cambridge University, Cambridge

The Engineering Laboratory at the University is regarded as the best technical institution in England. The testing facilities are excellent.

Prof. A. A. Townsend clarified the behavior of a turbulent boundary layer near separation (20). He showed that pressure distribution near the separation depends only on the pressure rise to separation and the characteristics of the initial boundary layer, and not on the geometry of flow.

Prof. W. A. Mair in the past worked on the flow separation caused by a spike mounted in front of a blunt body at supersonic speeds (21).

Dr. D. J. Maull, a young faculty member, conducted tests on the unsteady separation caused by a spike at Mach number of 2.8 (22) at Imperial College, London. The effect of the shape of the body nose on this unsteadiness was investigated, and an explanation of the mechanism of the oscillation given. An experiment on the cavity flow

is under way. The length of the oscillation wave is investigated with respect to  $b/a$ , a ratio of width to height of cavity. The research program on boundary layer control by suction is also in progress.

The study of position of separation on a blunt body in function of time is being made at Cambridge University.

B. France

Among the research institutions in France only the Office National D'Etudes et de Recherches Aéronautiques (ONERA) has been visited, because according to my information most of the research on flow separation has been done here.

ONERA

E. A. Eichelbrenner and associates have done excellent work on flow separation in the past. In 1954 the criterion of laminar three-dimensional boundary-layer separation was established in the form,  $\partial v^*/\partial n \Big|_p = 0$  where  $p$  designates the conditions on the wall,  $n$  is the coordinate normal to the wall, and  $v^*$  is the component along a certain direction of the velocity  $v$  inside the boundary layer (25).

In 1956, using a laminar two-dimensional airfoil NACA 64-A-015, the point of laminar separation was computed by Pohlhausen's method and compared with the experimental results. A good agreement on the location of separation was obtained, but downstream the agreement was rather poor. This indicated that Prandtl's hypothesis ceases to be valid in the immediate neighborhood of the separation point (24).

In 1959 the calculated separation line was compared with that obtained by visualization technique on a delta wing (25).

R. Legendre showed analytically that the separation line is neither an envelope of stream lines nor a locus of the points of these lines (26). However, as the experiment indicates, the separation line appears to be close to an envelope of the

stream line..

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P. Carrière and M. Girardix (27). A study is of compressible flow over the rearward facing step was made. They developed a computational method for studying the influence of certain factors which affect flow conditions under the curve of jet line. This method permits in particular the study of reattachment of non-uniform jet of revolution.

H. Werlé has been very successful conducting flow visualization experiments using colored milk and air bubbles in a water tank. The technique of visualization is applicable for various flow phenomena, for example, supersonic flow and ablation, etc. (28,29). Two colored films showing the flow visualizations were made at ONERA by Werlé.



Figure 1 The flow around an ogive at high angle-of-attack: visualization of the two vortices over the upper surface. These colored emissions show the external flow. (Photograph courtesy of ONERA)

C. Germany

The research institutes visited belong to the Institutes of Technology or Universities, and therefore the tests reported here are basic research.

1. Aerodynamische Versuchsanstalt--Göttingen

K. Kraemer investigated experimentally the base pressure behind a wedge at incidence with incompressible flow. He further investigated incompressible two-dimensional separated flows as shown in Fig. 2. By using conformal mapping lines of constant pressure in the neighborhood of separation point were obtained. For a circular cylinder assuming



Fig. 2. Models of Incompressible Separated Flows

the point of separation is known, and the separated region is small, velocity distribution around the circular cylinder in the presence of separation is determined. The solution is given by potential theory. The report of his work is underway, and will be published in Ingenieur Archiv soon.

2. Institut für Strömungsmechanik der Technischen Hochschule, Braunschweig

Under Prof. H. Schlichting the following researches were conducted:

(a) Cascades. H. Schlichting (3) states that the theory of cascades should be considerably extended to include viscosity effect in order to compute the smallest possible loss coefficient and the best possible efficiency. He outlined the way in which the aerodynamic coefficients of cascades are computed from the boundary layer theory. It is to be noticed that for optimum cascades the flow is partly separated in most cases.

Dr. K. Gersten investigated the influence of the Reynolds number on the flow losses in two-dimensional cascades. Generally the losses are decreased when the Reynolds number increases. At low Reynolds numbers separation of the laminar boundary layer takes place near the leading edge, and local separation of the laminar boundary layer encloses a bubble of turbulence. But a high Reynolds numbers separation of the turbulent boundary layer occurs near the trailing edge (31).

(b) Blowing: F. Thomas investigated experimentally the boundary layer control over-flap by blowing (32). Air is blown to prevent the separation and the blowing increases the lift considerably. He was successful in calculating the minimum momentum coefficient necessary to prevent boundary layer separation, and his calculation agrees well with experimental data up to a flap deflection of 45°.

(c) Separation on a Rotating Body: In addition, problems of separation, on a rotating body, of revolution and vortex flow over a delta wing are being investigated at the Institute.

### 3. Hermann Föttinger-Institut für Strömungstechnik,--Technische Universität, Berlin

Under the supervision of Prof. R. Wille, researches on turbulence are being conducted, since the Institut für Turbulenzforschung DVL is also located there. Prof. Wille critically surveyed the papers on Karman vortex streets, in particular the recent works in this field (33). In his paper he discussed, among others, his own references (34), those of U. Domm (35,36,37) and O. Wehrmann (38). They worked at this Institute under Prof. Wille. He also recently published a paper on Karman street (39). A. Timme studied the characteristics of vortex street and found that the Wehrmann method of splitting eddy strips is suited for giving more details on the character and density of eddies (40). Wehrmann measured accurately the values of amplitudes and frequencies in an axially symmetric jet downstream of a nozzle, by means of acoustical stabilization. He obtained a new interpretation of how the natural frequency

adjusts itself (41). H. Schade and A. Michalke investigated experimentally and theoretically the development of vortices in an axis symmetric jet downstream of a nozzle (42). They found that viscosity, though responsible for the formation of a shear layer, plays no significant role in the process of rolling up at high Reynolds numbers. A research program on transition is underway. The development of hot wire measurement is well advanced.

4. Institut für Schiffbau der Universität, Hamburg

Prof. K. Wieghardt found that a blunt rear end on an axial symmetric body resulted in lower total drag, though it caused a stronger separation, than did a narrowly tapered one (43). To my knowledge only this, among all the hydrodynamics institutes in Western Europe, is actively engaged in research in flow separation.

5. Aerodynamisches Institut, Technische Hochschule, Aachen

Construction of the Deutsche Versuchsanstalt für Luftfahrt (DVL) is in progress at the Cologne Airport near Wahn. Thus the research activities at Aachen will be enlarged and intensified, in combination with these large and modern research facilities.

In the past Prof. A. Naumann and Dr. A. Heyser experimentally studied supersonic flow separation. If gas flows through long and short pipes, then with a sharp-edged inlet a separation bubble makes the effective throat smaller than the pipe, and flow can be controlled to become critical (44). If a jet is ejected normal to a surface in supersonic flow then a detached shock and separated flow are formed, causing an effect similar to that of a solid protuberance normal to the wall. Thus, the jet spoilers in supersonic flight are subjects of investigation at Aachen at present. Wake flow studies at transonic flow regime were carried out in the past, and base pressure measurements behind bodies of revolution at supersonic speeds with large varieties of parameters are now in progress.

6. Technische Hochschule, Karlsruhe

Prof. A. Walz and D. Geropp studied the location of laminar separation in function of Mach numbers and heat transfer with stationary sinusoidal modulated outerstream (45). The results are as follows: For given amplitude and wave lengths of stream velocity, the location of separation shifts upstream if Mach number increases, and if the wall is cooled it then shifts downstream.

D. Italy

The research institute at Guidonia, active in the past, is no longer in operation. At present aerodynamics research is being done at the Scuola Ingegneria Aeronautica, Rome, headed by Prof. Luigi Broglio.

C. Buongiorno carried out experimental investigations on base pressure using sharp and blunt nosed models, and he obtained an interesting result on base pressure drag coefficients. For sharp nosed bodies the base pressure coefficients were negative as expected, but for a blunt nosed body the base pressure coefficient was measured as positive (46).

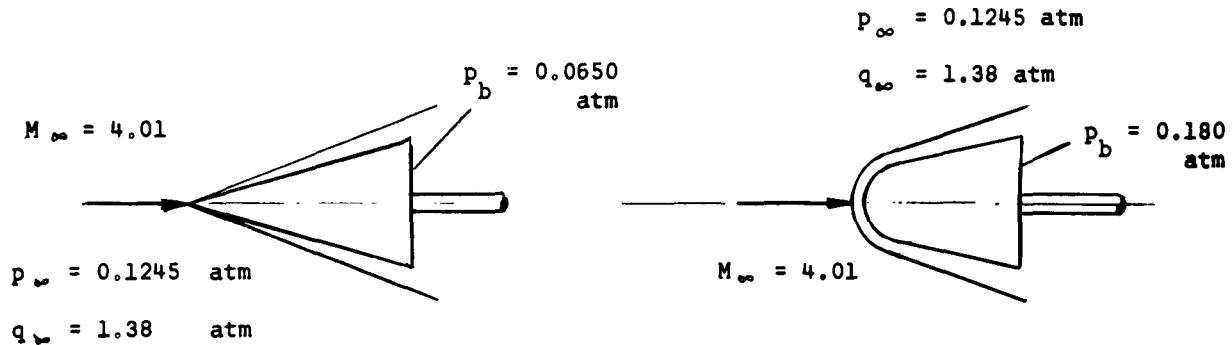


Fig. 3. Base Pressure

The base pressure coefficient

$$C_b = (p_\infty - p_b) / q$$

For sharp nosed body:  $C_b = -0.043$

For blunt nosed body:  $C_b = 0.040$

E. Belgium

Training Center for Experimental Aerodynamics--Rhode-Saint-Genese

Prof. J. J. Ginoux, who is also a professor at the University at Brussels, investigated the reattachment zone of a laminar separated boundary layer at Mach number 2.6. The model was a two-dimensional compression corner with backward or forward facing steps. He observed a strong regular and repeatable spanwise (i.e., three dimensional) perturbation in the boundary layer. He also found that in all cases the street-like flow perturbations existed up to the point where transition occurred (47). The leading edge effect at supersonic speed was investigated experimentally on a two-dimensional backward facing step model. It was found that there were regular spanwise perturbations in the full thickness of the boundary layer at and after reattachment both in laminar and turbulent flows. He concluded that the phenomenon is essentially one of instability in the two-dimensional flow, the main triggering action arising from small irregularities in the leading edge (48).

He further carried out experimental investigation at a Mach number of 2.2 on the effect of air injection in separated supersonic flow. The model was a two-dimensional backward facing step. An injection raised the base pressure and decreased the pressure gradient at reattachment. For turbulent flow the increase of the base pressure was larger than for laminar flow. When freon gas was injected, the effect was opposite, decreasing the base pressure (49).

F. Sweden

Flygtekniska Försökanstalten (FFA)--(The Aeronautical Institute of Sweden)

The institute is well equipped with research facilities and manpower despite the limited size of country and population.

E. G. M. Petersohn investigated the effect of boundary layer thickness on flow separation over the rear portion of bodies of revolution. He found that for slender

bodies the pressure drag decreases with the decreasing thickness of the boundary layer, but for less slender tails with strong separation, this tendency is not found. Experimental results can be used to estimate the drag due to separation at high Reynolds numbers (50).

H. Thomann measured heat transfer, recovery temperature, skin friction, and pressure distribution in the regions of separated flow produced by corners at Mach number 1.8. He found that the influence of separation on heat transfer and on recovery temperature was low (51). He studied vortex flow on a delta wing at  $M = 3$ .

#### G. Other Western European Countries

In Norway, Prof. J. K. Lunde, at Trondheim, Skipmodelltanken, has carried out experiments on flow separation in tunnel diffusors, and has tried to delay separation by rotating the water in the diffusor. In the Netherlands the well-known and well-equipped National Luchtvaart-Laboratorium, Amsterdam (National Aeronautical Research Institute), and in Denmark, Hydro-Og Aerodynamisk Laboratorium, Lyngby, headed by Prof. C. W. Prohaska, and Technical Institute, Copenhagen, are interested in the problems of flow separation, but no work has been done recently.

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#### Conclusions

In Western Europe the research activities on flow separation, particularly leading edge separation, the vortex flow, interaction between shock wave boundary layer and the general concept and formulation of flow separation are well advanced, and U. S. scientists will benefit by contacting the appropriate European scientists and research institutions. On the other hand, U. S. investigators will be in a

position to contribute to their European colleagues in the field of hypersonic flow separation. A close cooperation in research among the U. S. A., Europe, and elsewhere may expedite the solution of basic problems of flow separation, and make it possible to apply the physical phenomena effectively toward useful scientific and engineering development.

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